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A Simulation-based Evaluation of Selective and Adaptive Production Systems (SAPS) Supported by Quality Strategy in Production

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Abstract

Companies try to gain competitive advantages by creating customized products which meet customers' requirements and quality goals. Therefore, internal production processes need to be more effective in order to produce in required quality and shorter times at lower costs and act near to technological limits. Against this background the concept of SAPS provides an established approach of obtaining high precision assemblies from relatively low precision manufactured parts. This helps to lower production costs while providing high quality products. Since simulation is a useful support in planning and control, the paper presents an innovative simulation model that depicts the structure and function of SAPS as a production strategy dynamically.

Keywords: Quality strategies in production; Selective and Adaptive Production Systems (SAPS); Simulation

1. Introduction

High demands on the precision of products in manufacturing and assembly motivate the companies to search for a reasonable production strategy. One possibility is to increase the precision of individual manufactured parts, but this raises the costs sharply and is not always possible due to technical and economic restrictions. Numerous parameters affect the manufacturing accuracy and the manufacturing cost related to this accuracy such as machine tool capabilities, measurement uncertainty, tooling, inspection equipment, operator skill, lot size and scrap allowance [1]. The concept of SAPS aims at improving product quality and simultaneously reducing costs for quality [2]. This paper analyzes the SAPS concept dynamically by means of simulation as a production strategy supported by quality strategies in production. The goal is to achieve the highest rate of good assembled products at the minimum cost and shortest throughput time considering the production conditions and the available budgets.

2. Quality strategies in production

Economic Conformance Level (ECL): A cost minimizing quality level is proposed by this model [3]. This quality level is achieved by balancing prevention and appraisal costs against internal and external failure costs. Theoretically, the optimal economic conformance level is the proportion of non-defective products at which total costs are minimized. This can be achieved when the marginal prevention and appraisal costs equal the marginal failure costs [3].

Zero Defect Production: This strategy generally attempts to avoid all errors [3]. The cost per produced unit decreases continuously when the specifications are met better in the production process [4] [5]. In a zero defect strategy, a trade-off between fault avoidance and costs of defect correction, as in the ECL, is not possible. Thereby the considered indirect costs of bad quality are much higher than the considered direct costs. The focus

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is on preventing defects, with smooth continuous production as secondary goal after quality is achieved.

3. Selective and Adaptive Production Systems (SAPS)

As base for SAPS, the principle of the Adaptive and Selective Assembly (ASA) by Zocher [6] combines preventive and controlling quality assurance measures with the objective of Zero-Defect Production. This principle is used when the realizable manufacturing tolerance does not ensure the permissible tolerance of assembly. Key features of the ASA are the distribution of all parts in tolerance groups as well as the targeted combination of tolerance groups. The combination is based on algorithms and matching rules that comply with the resulting higher assembly tolerance requirements [2]. ASA by Zocher characterizes the concept of SAPS as shown in Fig. 1.

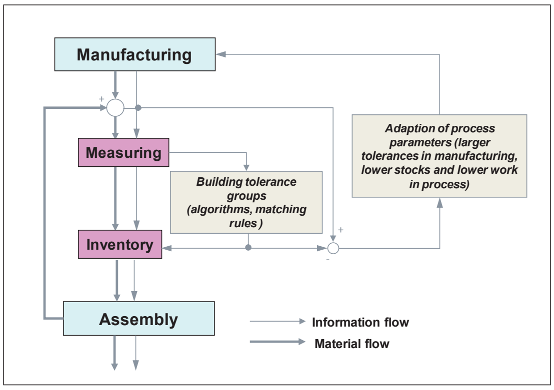

Fig. 1. Concept of Selective and Adaptive Production Systems in accordance with [6]

The difference between ASA and SAPS is that SAPS consider all production system elements and not just manufacturing and assembly elements. The selective component of SAPS is characterized by selective assembly based on predetermined classified groups, while the adaptive controlled influence of the process parameters in the manufacturing is the adaptive component of SAPS [2].

The selective assembly provides higher precision in the production system. However, significant re-installation costs could appear or some individual tolerance classes could run empty or a large number or size of inventories must be supplied. Through adaptive adjustment of parameters in the manufacturing of individual parts many of these problems and difficulties can be mitigated or even prevented.

The adaptive component tries to address this problem by seeking feedback from the results of the assembly that influence the process parameters at an earlier stage of production in a targeted way so that more parts can be assembled in the required quality. On the contrary to Zocher consideration, the adaptive part of ASA according to Lechner [7] can here be equated through local feedback loops, in which only the assembly strategy but not the process parameters is influenced.

Following from that, SAPS can be considered as a production strategy that maximizes the rate of good produced components, the rate of combined parts and minimizes the costs of waste, stocks, manufacturing machines, etc. Furthermore, SAPS can be implemented supported by quality strategies in production as follows:

- The Zero defect strategy can be applied for highly accurate manufacturing and measurement equipments in enterprises that have a large budget.
- Errors can be allowed in some elements of the SAPS (ECL) such as manufacturing machines that have a relatively low precision level. The proportion of non-defective products is maximized while total costs are minimized in enterprises that have a limited budget.

4. State of the art

SAPS approaches can be classified into static and dynamic approaches as shown in Fig. 2.

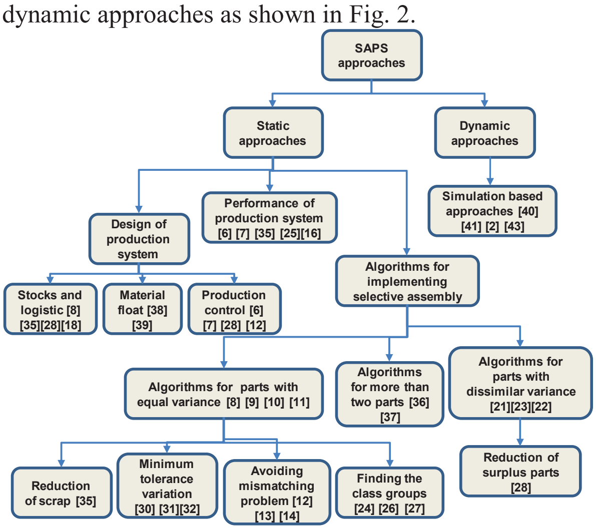

Fig. 2. Classification of SAPS approaches

Static approaches of SAPS can be described as follows: Most of the previous works focus on attaining the required assembly precision by employing equal width partitioning where every class has an equal width [8] [9] [10] [11]. Alternative schemes to avoid the mismatching problem are suggested [12] [13] [14]. Boyer introduced the Queuing Method in which a small number of parts is measured and queued [13]. Kulkarni and Garg presented a method to allocate the tolerance optimally in engineering designs, where simultaneous tolerance equations are used [15]. A method for evaluating the accuracy of a product based on a geometric design model was proposed by Arai [16]. Berzak discussed the robotic techniques in selective assembly to improve product quality and reduce the cost [17]. A high-speed station for selective assembly of high precision automotive components by maintaining small buffer storage of parts is introduced and evaluated [18]. A high precision assembly system based on the combination of selective assembly and micro machining through a combinatorial optimization method is proposed [19]. Carfagni developed a method for automatic tolerance allocation [20]. Kern introduced a general approach to selective assembly applicable when the distribution variations are different [21]. A solution is found in order to optimize tolerance synthesis of mechanical assemblies with alternative manufacturing processes [22]. Mease and Sudjianto presented the statistical framework for calculating the bin sizes that will minimize several loss functions and also showed optimal results from selective assembly by combining two unequal variance distributions [23]. Most of the papers are devoted to build algorithms, which aim at finding the class groups [24] [25] [26]. Chen developed a simplified algorithm to evaluate the optimal tolerances efficiently for enlarged mechanical component tolerances [27]. An algorithm to minimize the number of surplus parts by grouping the mating components based on balanced probability and unequal tolerance zone is presented [28]. Chase described a detailed algorithm for performing tolerance allocation automatically based on optimization techniques [29]. A heuristic approach of selective assembly for minimizing tolerance variation in which different algorithms are proposed to get a better and faster result is developed [30]. Kannan and Siva Kumar also developed the optimum manufacturing tolerance values to the selective assembly technique for different assembly specifications by using a genetic algorithm [31]. The authors suggested in another article a construction of closed-form equations and graphical representation for optimal tolerance allocation [32]. Beyond that, different special cases are analyzed in order to find rules for programming algorithms for these special cases [33] [34]. Chan and Linn proposed a grouping method based on a cumulative distribution function of the mating parts to ensure that matched parts meet the assembly specification while minimizing the number of scrapped components [35]. Iyama et al. used a Markov model to analyze a three-part ball bearing assembly. They found that the appropriate plan to produce components must consider both matching accuracy and the buffer capacity [36]. Kannan and Jayabalan conducted a study in linear assembly with three mating parts and developed a method to get required assembly tolerance with minimum surplus parts [37]. Besides algorithms there are approaches focusing on the material float, but not regarding the special needs of Selective and Adaptive Production Systems [38] [39].

Dynamic approaches of SAPS are rare and mostly simulation based approaches [40] [41] [42] [43] [2].

To illustrate the main focus of the presented research approaches in clear form, the approaches and the evaluation criteria are shown in matrix. Table 1 provides a comparison between considered SAPS approaches and adopted conditions that are previously presented.

Table 1. Comparison between SAPS approaches

	Considered assembling parts	**Classes division as batch size (b) or continuous (c)**	**Magnitude of the tolerance range: Various (/) or equal (=)**	**Considering the measurement inaccuracies**	**Adaptive control**	**Considering the stock**	**Considering the logistics**	**Increase the yield / avoidance of waste**	**Run empty tolerance classes**	**Dynamic view of one or two parameters**	**Dynamic view of many parameters and assembly strategies**
Mansoor	2	b	/.=	○	○	●	○	○	●	○	○
Desmond /Setty	2 ≤	b	=	○	●	○	○	○	○	○	○
Lechner	2	b		●	●	○	○	○	○	○	○
Pugh	2	b	/	○	○	○	○	○	○	○	○
Zocher	2	b		●	●	○	○	●	○	○	○
Fang/Zhang	2	b	/	○	●	●	○	●	○	○	○
Mease et al.	2	b	/	○	○	○	○	○	○	○	○
Iwata et al.	2	b		○	○	○	○	○	○	○	○
Coullard et	2	b		○	○	●	○	●	○	○	○
Thesen/ Jantayavich it	2	c	=	○	○	●	○	○	○	●	○
Kwon et al.	2	b	=	○	○	●	○	○	●	○	○
Chan. Linn	2	b	/	○		○	●	●	○	○	○
Kumar/ Kannan	2	b		○	○	○	○	●	○	○	○
Herrmann et al.	3	b		●	●	●	●	○	●	●	○
Halubek et al	3	b		●	●	○	●	○	○	●	○

An overview on the previous research proves that simulation-based approaches to show the dynamic influences between different criteria in the SAPS are rare. Those few simulation approaches just focus on only one parameter of influence in the production system, e.g. the logistic concept or the processes in manufacturing.

This paper tries to cover the gaps in previous research by considering different assembly strategies and many parameters together such as manufacturing and measurement capability, throughput time and the number of tolerance classes which influence together the performance of SAPS.

5. Simulation approach

The goal of the simulation approach by constructing the simulation model is the simultaneous dynamic consideration of many parameters and factors which have different effects on the elements and productivity of SAPS and integrates different interdependent criteria defining the efficiency of SAPS. The model consists of different modules, which cover the different areas of the production system. The manufacturing department, the production control and the assembly level that include transport system and final assembly are the structure of the simulation model.

These modules consist inherently of production system elements such as manufacturing, measurement, assembly, transport, information, material flow, control, etc. These elements are included in each module and each element consists of embedded objects as queues, delays, combine, match, sink, etc. and activities such as parameters, plain variables, dynamic variables, events, connectivity and functions. Fig. 3 illustrates the elements of SAPS simulation model affected by quality strategies in accordance with [44].

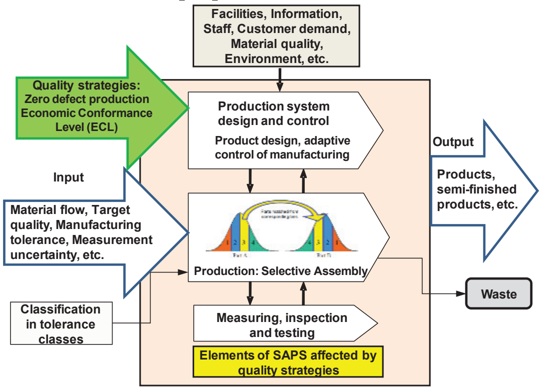

Fig. 3. The elements of SAPS simulation model affected by quality strategies in accordance with [44]

The embedded objects and activities are modeled so that their properties can be individually configured as input parameters. Fig. 4 illustrates the input data, modules and evaluation criteria of the simulation model. Several input parameters are possible such as dimension target, manufacturing tolerance, human error, material selection, measurement capability, etc. in the manufacturing module. Furthermore, number of tolerance classes, tolerance class width, altered dimension target, etc. can be controlled in the production control module. In addition, classification rules, target quality, assembly measurement uncertainty and assembly range can be entered in the assembly module. The assessment criteria of the production system performance can be considered as output data:

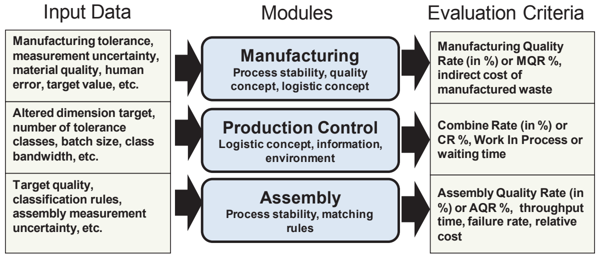

Fig. 4. Input data, modules and evaluation criteria of the SAPS simulation model

- The Assembly Quality Rate (in %) or AQR % that indicates the share of good assembled products or failure-rate.
- The Combine Rate (in %) or CR % that indicates the proportion of performed assembly and indirectly the waiting-time and work in process (WIP).
- The throughput time that indicates the required period for part to pass through the production process.

AnyLogic by XJ Technologies is the used software tool to implement the simulation model. Besides modeling the logic structure of the simulation, a graphical user interface was developed. Fig. 5 describes the simulation environment and workflow of the model.

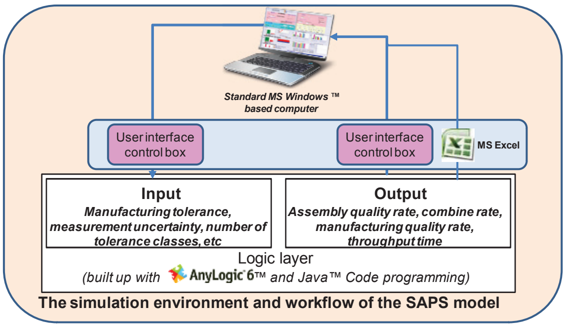

Fig. 5. The simulation environment and workflow of the SAPS model

6. Exemplary application

The study will be carried out in an exemplary application in which two parts are assembled together to form a product. The mentioned input parameters will be changed based on ceteris paribus method and according to a reference scenario. In each scenario, the number of assembled components is 5000 and the accepted assembly range in the final assembly is 18µm. Different scenarios aim at increasing the performance of the production system through increasing the share of good assembled products and reducing the work in process (WIP), has been used in order to evaluate the model by the systematic variation of input parameters.

Fig. 6 shows the effect of manufacturing and measurement capability on AQR % and CR %.

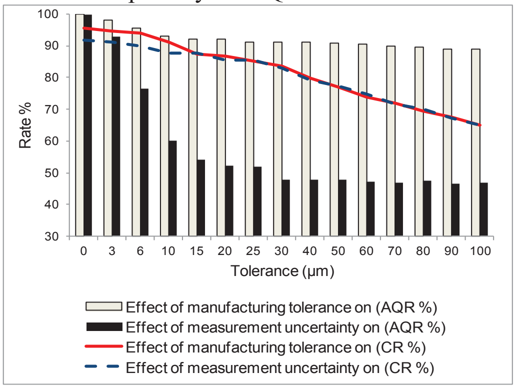

Fig. 6. Effect of manufacturing and measurement capability on AQR % and CR %

The investment on measurement accuracy is more effective than manufacturing accuracy in the accuracy range between 0-25µm because the assembly quality rate seems to be stable in the range between 25-100µm. That means that optimal solutions regarding limited budgets can be found. For example, manufacturing machines with relatively low accuracy can be used with high measurement accuracy machines under specific conditions to achieve the targeted performance. From this, implementing SAPS strategy using high accurate measuring technology with measurement uncertainty of 3µm optimizes the assembly quality in the amount of 39% in compare with using middle accurate measuring technology with measurement uncertainty of 15µm.

The influence of manufacturing and measurement capability on CR % and indirectly on work in process (WIP) is approximately similar by tolerance more than 15µm (Fig. 6). The improvement in manufacturing tolerance leads to an optimization of almost 6% in CR % in compare with the measurement uncertainty under specific manufacturing tolerance and measurement accuracy (less than 15 µm).

Fig. 7 shows how the number of tolerance classes affect AQR %, CR % and mean throughput time. Increasing the number of tolerance classes to a specific limit (in our case 12 classes) leads to an improvement regarding AQR %, but that will increase the waiting time and throughput time. Therefore, the adaptive production control tries to fill the run empty classes in the right time which reduce the waiting time and work in process.

The local optimum of combination between available manufacturing and measurement accuracy and the relevant number of tolerance classes considering the class bandwidth improves the productivity of the production system. For example: with manufacturing tolerance 52µm, measurement uncertainty 2µm, number of tolerance classes 12, assembly measurement uncertainty 2µm and required quality range in the final assembly 18µm we have an amount of 93.48% good assembled products and 23% work in process.

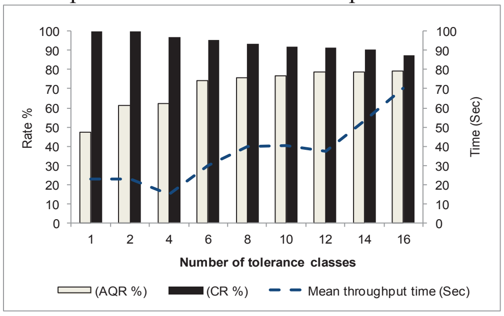

Fig. 7. Effect of number of tolerance classes on AQR %, CR % and throughput time

Considering the cost, the third assessment dimension of SAPS, a manufacturing tolerance = 3µm is needed by random assembly, which is difficult to achieve in reality, in order to get the same output or the same rate of good assembled products comparing with a manufacturing tolerance = 52µm by SAPS. That means: The saved relative costs of manufacturing machine in SAPS are approximately six times more than in a random production system. The saved costs can be used to improve the accuracy of measuring system in SAPS.

7. Summary

The focus of this paper was to suggest and analyze the SAPS concept dynamically as a production strategy supported by quality strategies. Based on this concept the simulation model is designed according to its individual modules and the inter-connections between them and then implemented in concrete software AnyLogic. The case study is applied to a fictitious example and carried out by various tests and scenarios to identify fundamental causal relationships between many effecting factors. It is important to mention that the simulation approach is for a specific case under specific conditions and distinctive parameters. The final assessment concludes that the designed simulation model is suitable to depict the effect of manufacturing and measurement capability and the number of tolerance classes on the performance of SAPS dynamically and estimate initially the efficiency of SAPS at an early stage of production planning. In order to make simulation an effective tool for production planning and production system design in the future, hybrid approaches that integrate analytical methods and computer simulation should be proposed in an effort to achieve the advantages of both while avoiding their disadvantages.

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